ELSEVIER

Soil & Tillage Research 34 (1995) 95–104

Soil & Tillage Research

A method to predict bulk density of tilled Ap horizons

T.G. Reinsch*, R.B. Grossman

USDA–SCS, 100 Centennial Mall North, Lincoln, NE 68508, USA

Accepted 6 January 1995

Abstract

Bulk density of the Ap horizon is dynamic with respect to time and land use and therefore multiple field measurements are necessary to characterize it. Researchers often need a bulk density value to use in models, characterize field conditions, or convert gravimetric to volumetric measurements. A method is described to predict the field bulk density of the Ap horizon by measurement of the bulk density in the laboratory. The bulk density value measured with this method is independent of the use and temporal dynamics of the tillage zone. The method involves four treatments that have application in predicting bulk density values irrespective of the soil condition when sampled were tested. The treatments are: (1) capillary wetting and desorption at 33 kPa suction; (2) capillary wetting, inundation, air drying, rewetting by capillary action, and desorption at 33 kPa suction; (3) Treatment 2 followed by oven drying; (4) standard mechanical compaction at various water contents to obtain the Proctor density. Bulk densities for Treatments 1–3 were similar for soils with coefficient of linear extensibility less than 0.01. Bulk densities for Treatment 3 were similar to interpretive values used by the USDA–SCS and values predicted from Gupta and Larson's (Soil Sci. Soc. Am. J., 43: 758–764, 1979) packing model. Bulk densities for Treatment 2 are similar to field measurements. Comparison of bulk densities for Treatment 2 and field measurements provide an evaluation of soil health.

Keywords: Bulk density; Capillary wetting; Inundated bulk density; Proctor density; Water Erosion Prediction Project (WEPP)

1. Introduction

Bulk density is an estimated soil property in the soil interpretations record (SIR) of the US Department of Agriculture–Soil Conservation Service (USDA–SCS). In the SIR, soil property estimates are reported as ranges and are based on the expected variation within the

* Corresponding author. e-mail: tgr@nssc600.nssc.nrcs.usda.gov

SSDI 0167-1987(95)00458-0

modal concept of the named soil and analytical variation (Soil Survey Division Staff, 1993). However, the ranges assigned in the SIR to Ap horizons do not address the difference owing to land use nor the changes over time for a given land use.

The standard bulk density measurement in the USDA–SCS is the clod method using a flexible coating (Brasher et al., 1966). The method permits determination of the bulk density at various soil water contents. This method has not produced a satisfactory database for bulk density of Ap horizons. One reason is that if the soil is mechanically disturbed, the soil is not always sufficiently cohesive to obtain clods. Another reason is that sites are usually sampled only once and therefore the measured bulk density for the tillage zone reflects the immediately previous treatment of the soil, such as plowing, seedbed preparation, cultivation, and harvest, or the meteorological effects such as freeze–thaw cycles, raindrop impact, and wetting–drying cycles.

Bulk density can be measured in the field using cores or by excavation techniques (Blake and Hartge, 1986). It is difficult, however, to sample loose, tilled soil with cores. Excavation methods are effective for measuring bulk density in the field. However, the limitations of this technique are that a soil water retention curve cannot be measured on the undisturbed sample and that, as bulk density is measured at only one soil water content, the coefficient of linear extensibility (COLE) cannot be determined (Grossman et al., 1968).

Empirical equations (Alberts et al., 1989; Baumer, 1992) have been proposed to predict bulk density. These equations are based on bulk density values obtained by the clod method (Brasher et al., 1966). Furthermore, the database contains bulk density values only for horizons on which it was possible to obtain clods, thus biasing the sampling toward Ap horizons that have some degree of cohesiveness.

Gupta and Larson (1979) proposed a model for predicting the dry bulk density of soil. The particle-size distribution and organic matter content are used in the model to calculate a random packing density. The random packing model is also used to predict a distribution of bulk densities including the maximum, minimum, mean, and first, second, and third quartile bulk density estimates.

Four bulk density treatments are presented that can be used irrespective of the soil condition at sampling time. These treatments provide bulk density and derivative quantities such as COLE under standardized water compaction using the less than 2 mm soil as prepared for general soil analysis. The treatments are applicable to large-scale production, and the measured bulk density values can be used in process models to simulate soil conditions and their effect on crop yield and ecological processes. Bulk density values obtained from the four treatments are compared against the estimated bulk densities from SIRs, from prediction equations, and bulk density from field measurements to identify a treatment that provides reproducible bulk densities.

2. Methods

Four treatments of measuring bulk density were tested on the 33 soils listed in Table 1. These soils were from the cropland experimental sites for the USDA Water Erosion Prediction Project (WEPP). All sites were sampled using pedological methods before tillage for the erosion experiments. The soil classification is of the sampled pedon. Where the

Table 1
WEPP soil series, location, and pedon classification

Series	Location	Classification
Academy	Fresno, CA	Fine-loamy, mixed, thermic Mollic Haploxeralf
Amarillo	Big Springs, TX	Fine-loamy, mixed, thermic Aridic Paleustalf
Anselmo	Ord, NE	Coarse-loamy, mixed, mesic Typic Haplustoll
Barnes–MN	Morris, MN	Fine-loamy, mixed Udic Haploboroll
Barnes–ND	Goodrich, ND	Fine-loamy, mixed Udic Haploboroll
Bonifay	Tifton, GA	Loamy, siliceous, thermic Grossarenic Plinthic Paleudult
Caribou	Presque Isle, ME	Fine-loamy, mixed, frigid Typic Haplorthod
Cecil	Watkinsville, GA	Clayey, kaolinitic, thermic Typic Kanhapuldult
Collamer	Ithaca, NY	Fine-silty, mixed, mesic Glossaquic Hapludalf
Frederick[a]	Hancock, MD	Fine, mixed, mesic Typic Hapludalf
Gaston[a]	Salisbury, NC	Fine, kaolinitic, thermic Typic Kanhapudult
Grenada[a]	Como, MS	Fine-silty, mixed, thermic Typic Fragiochrept
Heiden	Waco, TX	Fine, montmorillonitic, thermic Udic Haplustert
Hiwassee[a]	Watkinsville, GA	Clayey, kaolinitic, thermic Rhodic Kanhapludult
Keith	Albin, WY	Fine-silty, mixed, mesic Aridic Argiustoll
Lewisburg	Columbia City, IN	Fine, mixed, mesic Aquic Hapludalf
Los Banos[a]	Los Banos, CA	Fine, montmorillonitic, thermic Typic Haploxeroll
Manor	Ellicot City, MD	Coarse-loamy, micaceous, mesic Typic Dystrochrept
Mexico	Columbia, MO	Fine, montmorillonitic, mesic Mollic Endoaqualf
Miami	Waveland, IN	Fine-loamy, mixed, mesic Typic Hapludalf
Miamian	Dayton, OH	Fine, mixed, mesic Typic Hapludalf
Nansene	Pullman, WA	Coarse-silty, mixed, mesic Pachic Haploxeroll
Opequon[a]	Flintstone, MD	Fine, mixed, mesic Typic Hapludalf
Palouse	Pullman, WA	Fine-silty, mixed, mesic Pachic Ultic Haploxeroll
Pierre	Wall, SD	Fine, montmorillonitic, mesic Aridic Haplustert
Portneuf	Twin Falls, ID	Coarse-silty, mixed, mesic Durixerollic Calciorthid
Sharpsburg	Lincoln, NE	Fine, montmorillonitic, mesic Typic Argiudoll
Sverdrup	Morris, MN	Sandy, mixed Udic Haploboroll
Tifton	Tifton, GA	Fine-loamy, siliceous, thermic Plinthic Kandiudult
Whitney	Fresno, CA	Fine-loamy, mixed, thermic Mollic Haploxeralf
Williams	McClusky, ND	Fine-loamy, mixed Typic Argiboroll
Woodward	Buffalo, OK	Coarse-silty, mixed, thermic Typic Ustochrept
Zahl	Bainville, MT	Fine-loamy, mixed Entic Haploboroll

[a]Taxadjunct.

pedon classification does not match the classification of the series identified, the pedon is indicated as a taxadjunct. Physical measurements for the Ap horizons after tillage for the experiments have been given by Elliot et al. (1989). Bulk soil samples also were collected shortly after tillage and before the erosion experiments. These samples are different from the samples collected for pedological characterization. The gravimetric water contents and excavation bulk density of the Ap horizons also were measured at each site after tillage, and before and after simulated rainfall (Elliot et al., 1989).

Table 2 contains representative soil characteristics for the Ap horizons as sampled before tillage using USDA–SCS methods (Soil Survey Staff, 1991): clay and sand, pipet method (Gee and Bauder, 1986); water retention at 1500 kPa (Gardner, 1986); organic carbon, modified Walkley–Black (Nelson and Sommers, 1982); cation exchange capacity,

Table 2
Selected soil characteristics

Series	Clay (%)	Sand (%)	Organic carbon (dg kg^{-1})	CEC7 (cmol kg^{-1})	Water retention at 1500 kPa (dg kg^{-1})	Bulk density (Mg m^{-3})
Academy	13.6	63.0	0.34	5.2	3.6	1.81
Amarillo	7.5	86.5	0.14	5.0	3.1	1.77
Anserlmo	6.8	82.1	0.40	4.6	3.2	1.63
Barnes—MN	7.7	76.3	1.21	10.7	5.0	1.48
Barnes—ND	25.3	42.2	2.52	22.4	13.1	1.33
Bonifay	3.7	91.9	0.25	1.6	0.8	1.64
Caribou	14.2	46.0	1.84	11.9	8.6	1.49
Cecil	33.6	51.8	0.66	5.3	12.8	1.79
Collamer	17.0	4.8	1.06	9.2	7.6	1.39
Frederick	16.8	22.0	1.23	9.5	7.0	1.52
Gaston	50.3	25.8	1.09	10.2	19.2	1.57
Grenada	20.4	3.5	0.99	13.0	9.9	1.50
Heiden	53.3	8.9	1.36	38.1	20.6	1.40
Hiwassee	15.7	65.8	0.50	3.5	5.3	1.63
Keith	17.8	47.3	0.94	16.3	10.6	1.48
Lewisburg	18.5	40.1	0.88	12.4	9.3	1.70
Los Banos	49.4	15.7	1.45	37.7	17.3	1.40
Manor	24.6	44.2	0.97	11.8	11.6	1.53
Mexico	22.1	4.6	1.55	19.2	10.0	1.41
Miami	15.9	4.4	0.79	13.8	9.2	1.61
Miamian	30.5	30.4	2.01	16.8	12.4	1.97
Nansene	13.6	18.0	1.34	16.5	8.7	1.25
Opequon	32.9	12.1	1.50	13.0	13.2	1.31
Palouse	22.1	8.3	1.35	20.5	10.6	1.36
Pierre	48.7	11.5	1.35	38.9	1.7	1.32
Portneuf	9.7	16.1	0.77	12.5	9.3	1.33
Sharpsburg	41.0	2.4	1.70	28.5	20.0	1.37
Sverdrup	22.6	46.9	1.54	16.4	8.6	1.60
Tifton	4.7	86.5	0.43	2.7	1.6	1.80
Whitney	6.7	75.0	0.27	5.0	3.2	1.80
Williams	26.9	41.8	1.61	20.9	14.1	1.45
Woodward	12.0	48.5	0.75	11.4	6.3	1.43
Zahl	29.8	46.4	1.70	22.0	10.1	1.56

NH_4OAc, pH 7.0 (CEC7) (Peech et al., 1947) and the bulk density at 33 kPa suction for clods collected in the field (Blake and Hartge, 1986). The ratio of CEC7 and clay is used to estimate clay activity, which is a parameter in the DMSOIL equation.

Bulk densities (Table 3) were measured on cores formed in the laboratory of less than 2 mm soil that had been subject to different water state histories. The wetting treatments of soil before bulk density measurement are designed to simulate the influence of the water state patterns on the bulk density of Ap horizons after mechanical disturbance. The treatments were: (1) capillary wetting and desorption at air pressure of 33 kPa; (2) capillary wetting, inundation, air drying, rewetting by capillary action, and desorption at air pressure of 33 kPa; (3) Treatment 2 followed by oven drying; (4) the maximum bulk density (Proctor density, ASTM D 698-91, 1992) using standard mechanical compaction at various

Table 3
Bulk density (in Mg m^{-3}) measured after treatments and coefficient of linear extensibility (COLE)

Soil	Average bulk density				COLE
	Capillary (33 kPa)	Inundation (33 kPa)	Oven dry	Proctor	
Academy	1.66	1.69	1.69	1.99	0.001
Amarillo	1.44	1.53	1.55	1.90	0.006
Anselmo	1.41	1.57	1.59	n.d.[a]	0.005
Barnes—MN	1.39	1.44	1.47	n.d.	0.008
Barnes—ND	1.09	1.17	1.27**	1.59	0.027
Bonifay	1.56	1.66	1.67	1.77	0.002
Caribou	1.12	1.23	1.26**	1.60	0.010
Cecil	1.13	1.28	1.34**	1.73	0.015
Collamer	1.20	1.39**	1.43**	1.65	0.010
Frederick	1.16	1.26*	1.30**	1.59	0.011
Gaston	1.04	1.14*	1.29**	1.58	0.041
Grenada	1.17	1.31**	1.40**	1.65	0.022
Heiden	1.01	1.07	1.29**	n.d.	0.064
Hiwassee	1.36	1.50*	1.52*	n.d.	0.005
Keith	1.08	1.21*	1.27**	1.63	0.016
Lewisburg	1.25	1.38	1.47*	n.d.	0.020
Los Banos	1.04	0.99	1.25**	1.53	0.082
Manor	1.05	1.19**	1.26**	1.65	0.020
Mexico	1.10	1.21	1.32*	1.58	0.031
Miami	1.20	1.30*	1.38	1.68	0.020
Miamian	1.16	1.23*	1.37**	1.65	0.037
Nansene	1.19	1.30	1.33	n.d.	0.009
Opequon	1.10	1.27**	1.34**	1.55	0.018
Palouse	1.09	1.25*	1.34**	1.65	0.023
Pierre	0.96	1.00*	1.22**	1.47	0.068
Portneuf	1.24	1.31	1.34**	1.53	0.008
Sharpsburg	1.10	1.19**	1.46**	1.48	0.070
Sverdrup	1.21	1.27	1.35*	1.67	0.021
Tifton	1.51	1.61**	1.61	1.90	0.001
Whitney	1.45	1.62*	1.64	1.99	0.004
Williams	1.09	1.15	1.28**	1.79	0.036
Woodward	1.22	1.37	1.42*	1.79	0.012
Zahl	1.15	1.19	1.28**	1.67	0.025
Overall					
Mean	1.21	1.31**	1.39**	1.68	
SE	0.04	0.03	0.03		

[a]n.d., not determined. *,**Significant difference between capillary and inundation treatments or inundation and oven-dry treatments at $P=0.05$ and $P=0.01$, respectively.

soil water contents. The coefficient of linear extensibility (COLE) was determined using the inundation and oven-dry bulk densities (Grossman et al., 1968).

2.1. Treatment 1, capillary wetting

Soil cores were formed in a cell made by attaching a brass ring or schedule 40 PVC pipe, of 5.4 cm diameter and 6 cm height, to a 100 kPa ceramic plate with waterproof glue and

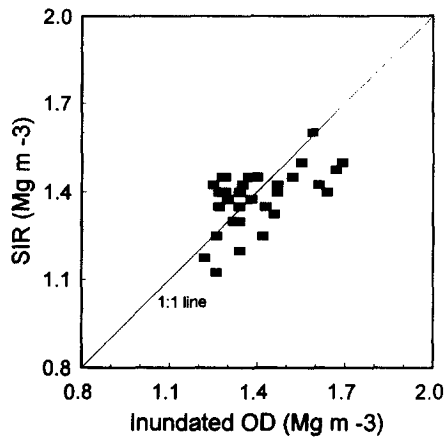

Fig. 1. Bulk density of midpoint of soil interpretation record (SIR) range and measured on inundated cores.

caulk. The volume of the cell was determined. An additional ring, of 5.4 cm diameter and 3 cm height, was attached with waterproof tape. A wire screen with 0.5 cm openings and 5.2 cm diameter with a perpendicular wire attached to the center was placed in the cell. Soil passed through a 2 mm sieve (No. 10) was added until the soil level exceeded the height of the lower ring. The wire screen was then lifted out of the cell to reduce differential packing. The soil was moistened on a tension table made of porous ceramic bricks with a constant water level of 5 cm below the top of the brick. The ceramic bricks are covered with reinforced paper towels to provide contact with the ceramic plate at the base of the cell. The soil was then desorbed to equilibrium in a pressure chamber at 33 kPa. After desorption the added top ring was removed. The part of the soil core that extended above the cell was then cut off with a sharp knife. Gravimetric water content was determined on the removed soil. The remainder of the cell and soil was weighed. The volume of the cell was adjusted for soil shrinkage on capillary wetting by measuring the gap, if any, between

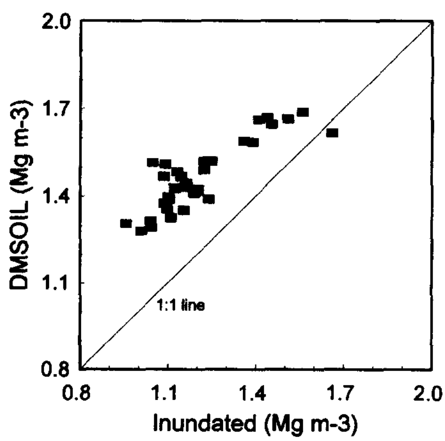

Fig. 2. Bulk density predicted by DMSOIL model vs. inundated core bulk density.

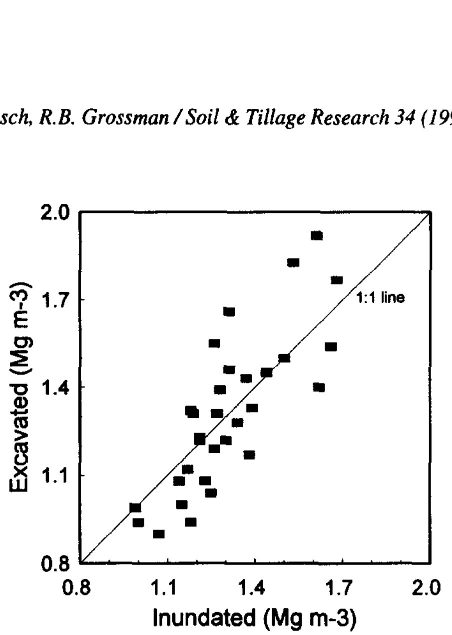

Fig. 3. Bulk density from compliant cavity measured at WEPP sites and inundated cores.

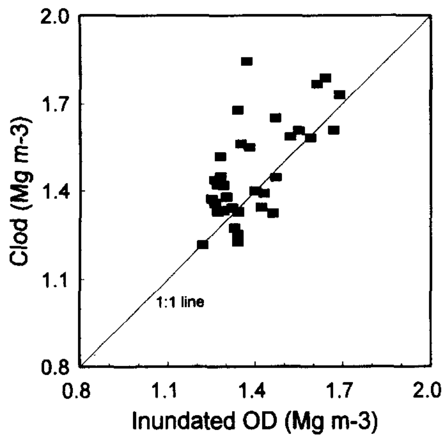

Fig. 4. Bulk density from clods collected at the WEPP sites and inundated cores.

Table 4
Comparison of Gupta and Larson packing model and bulk density treatments

Comparison	Mean	SD	*t*	*t* COLE < 0.06
Pack(mean)–inun(od)	0.009	0.014	0.63	0.70
Pack(0.5)–inun(od)	0.005	0.015	0.35	0.42
Pack(0.25)–inun(od)	−0.04	0.014	−2.56*	−2.37*
Pack(mean)–inun(33)	0.09	0.019	4.96**	4.26**
Pack(min)–cap(33)	0.05	0.017	3.01**	2.34
Pack(max)–Proctor	−0.11	0.021	−5.19**	−5.22**
Pack(0.25)–inun(33)	0.05	0.018	2.50*	1.61

*,**Significant difference at $P = 0.05$ and $P = 0.01$, respectively.

the soil and cell wall with thin metal strips of known thickness (feeler gauge). The oven-dry weight of the soil was calculated by subtracting the percentage of water in the soil removed from the core top.

2.2. Treatments 2 and 3, inundation and oven drying

The inundation bulk density was determined on the same sample after the capillary wetted measurement by reattaching the top ring with waterproof tape. The soil was moistened again on a tension table made of porous ceramic bricks with a constant water level of 5 cm below the top of the brick, followed by inundation from beneath and subsequent air drying. The soil was removed from the cell as an intact core. The core was coated with flexible plastic (Brasher et al., 1966), then cut to expose soil, and moistened at 0.5 kPa suction. The core was then desorbed to 33 kPa suction in a pressure plate apparatus (Richards, 1947; Soil Survey Staff, 1991). If the soil could not be removed from the cell as an intact core, as for example some sandy soils, the soil was moistened and desorbed in the cell, as in the capillary wetting treatment. The gravimetric water content and the bulk densities at 33 kPa suction and oven dry were determined.

2.3. Treatment 4, Proctor density

The maximum Proctor density was determined on 20 kg field samples. The samples were passed through a 2 mm sieve (no. 10) prior to the measurement. The use of the less than 2 mm soil is a departure from the standard procedure (ASTM D 698-91, 1992).

Data from the treatments and estimated by models were compared using the paired t-test described by Snedecor and Cochran (1980) and the GLM procedure (Statistical Analysis Systems (SAS) Institute, Inc., 1988).

3. Results and discussion

The average values of bulk density for three soil treatment conditions and the Proctor bulk density are reported in Table 3. The three treatment measurements were each replicated three times. Analysis of variance using a nested or hierarchical classification (Snedecor and Cochran, 1980; SAS Institute, Inc., 1988) of soil, soil treatment, and replications indicates that there is no interaction among replicates, soil, or soil treatment, but there is significant difference among the treatments and soils at the 0.01 probability level. Capillary and inundation treatments and inundation and oven-dry treatments were compared using t-test. Significant difference between the capillary and inundation treatments is shown in Table 3 for 15 of the 33 soils. Significant differences between the inundation and oven-dry treatments are also shown. The treatments were similar for soils that had a COLE < 0.01 except for the Hiwassee and Portneuf soils.

The capillary, inundated, and oven-dry bulk density values were compared with the estimated bulk densities in the soil interpretation record. There were no significant differences ($P = 0.05$) between the minimum interpretive values and the capillary and inundated bulk density values, and between the midpoint of the interpretive values and the oven-dry bulk density (Fig. 1).

The DMSOIL model (Baumer, 1992) predicts consistently higher bulk densities than the inundated bulk densities (Fig. 2). The DMSOIL and inundated values are significantly different at $P=0.001$.

Fig. 3 compares the treatments with bulk density measured by excavation methods (Bradford and Grossman, 1982) at the WEPP sites before and after simulated rainfall. There is no significant difference ($P=0.05$) between the bulk density after simulated rainfall and the inundation cores. This suggests that the inundation bulk density is a good approximation of field bulk density after mechanical disturbance followed by very high rainfall.

Fig. 4 compares treatment bulk densities with the field clod bulk densities for the Ap horizons (Table 1). The field bulk densities were measured using soil clods coated with plastic. All treatment bulk densities were significantly different ($P=0.05$) from the clod bulk densities. The inundated bulk density provides a baseline reference. Changes in the differences between the field bulk density and inundated bulk density should be explored as a descriptor of soil health.

Table 4 compares the bulk densities calculated using a packing model (Gupta and Larson, 1979) with the treatments. There was no significant difference ($P=0.01$) between the mean and the mode of the packing bulk densities and the inundated oven-dry bulk density. The packing model does not account for shrink–swell properties of soil, therefore a coefficient of linear extensibility (COLE) of 0.06 was chosen to separate the soils into two groups. For the group of soils with COLE <0.06, there is no significant difference ($P=0.05$) between the minimum packing bulk density and the capillary bulk density. Neither is there between the 25 quartile packing bulk density and the inundated bulk density at 33 kPa.

4. Conclusion

Bulk densities of clods fabricated from less than 2 mm soil material coupled with Proctor density are useful to predict the bulk density changes of Ap horizons owing to alterations in the water state and mechanical compaction. The bulk density after capillary wetting is an indicator of field condition after tillage and before compaction by rain. The bulk density after inundation, subsequent drying, and rewetting to 33 kPa retention is conceived to be applicable to a tillage zone that has been tilled followed by heavy precipitation with the presence of free water and a subsequent drying event followed by rewetting. The oven-dry bulk density after inundation permits calculation of linear extensibility. In the Proctor method, bulk densities at various water contents and degrees of compaction may be useful to predict the bulk density expected in the mechanically compacted zone for combinations of tillage operations and antecedent water states.The mean bulk density estimated by the Gupta and Larson packing model is an acceptable approximation of the oven-dry bulk density after inundation.

For Ap horizons, the inundation bulk density and associated COLE should be considered for addition to the soil interpretation record. The approach largely removes the effect of temporal change of bulk density. Comparison of the inundation bulk density at 33 kPa with the near-surface field bulk density at the same suction may provide an evaluation of soil health.

Acknowledgments

Laboratory analysis was done by Larry Arnold. Proctor density was done at the USDA–SCS Soil Mechanics Laboratory, Lincoln, NE, directed by Phillip N. Jones.

References

Alberts, E.E., Laflen, J.M., Rawls, W.J., Simanton, J.R. and Nearing, M.A., 1989. Soil component. In: L.J. Lane and M.A. Nearing (Editors), USDA—Water Erosion Prediction Project: hillslope profile model documentation. NSERL Rep. 2, USDA-ARS, West Lafayette, IN.

ASTM D 698-91, 1992. Test method for laboratory compaction characteristics of soil using standard effort (12 400 ft-lbs/ft^3 (600 kN-m/m^3)). In: 1992 Annual Book of ASTM Standards. Sec 4. Construction. Vol. 04.08. Soil and Rock: Dimension Stone: Geosynthesis. ASTM, Philadelphia, PA.

Baumer, O.W., 1992. Prediction of soil hydraulic parameters. In: Indirect Methods for Estimating the Hydraulic Properties of Unsaturated Soils: Proc. Int. Workshop on Indirect Methods for Estimating the Hydraulic Properties of Unsaturated Soils, Riverside, CA, 11–13 October 1989. US Salinity Lab. USDA-ARS, Riverside, CA, and Dept. of Soil and Environmental Sciences, Univ. of Calif., Riverside, pp. 341–354.

Blake, G.R. and Hartge, K.H., 1986. Bulk density. In: A. Klute (Editor), Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods. 2nd edn. Agronomy, 9. American Society of Agronomy, Madison, WI, pp. 363–382.

Bradford, J.M. and Grossman, R.B., 1982. In-situ measurement of near-surface soil strength by the fall-cone device. Soil Sci. Soc. Am. J., 46: 685–688.

Brasher, B.R., Franzmeier, D.P., Valassis, V.T. and Davidson, S.E., 1966. Use of Saran resin to coat natural soil clods for bulk density and water retention measurements. Soil Sci., 101: 108.

Elliot, W.J., Liebenow, A.M., Laflen, J.M. and Kohl, K.D., 1989. A compendium of soil erodibility data from WEPP cropland soil field erodibility experiments 1987 and 1988. NSERL Rep. 3. USDA-ARS, West Lafayette, IN.

Gardner, W.H., 1986. Water content. In: A. Klute (Editor), Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods, 2nd edn. Agronomy, 9. American Society of Agronomy, Madison, WI, pp. 363–382.

Gee, G.W. and Bauder, J.W., 1986. Particle-size analysis. In: A. Klute (Editor) Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods, 2nd edn. Agronomy, 9. American Society of Agronomy, Madison, WI, pp. 383–411.

Grossman, R.B., Brasher, B.R., Franzmeier, D.P. and Walker, J.L., 1968. Linear extensibility as calculated from natural-clod bulk density measurements. Soil Sci. Soc. Am. Proc., 32: 568–570.

Gupta, S.C. and Larson, W.E., 1979. A model for predicting packing density of soils using particle-size distribution. Soil Sci. Soc. Am. J., 43: 758–764.

Nelson, D.W. and Sommers, L.E., 1982. Total carbon, organic carbon, and organic carbon. In: A.L. Page (Editor), Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties, 2nd edn. Agronomy, 9. American Society of Agronomy, Madison, WI, pp. 539–580.

Peech, M., Alexander, L.T., Dean, L.A. and Reed, J.F., 1947. Methods of soil analysis for soil fertility investigations. US Dep. Agric. Circ. 757, 25 pp.

Richards, L.A., 1947. Pressure-membrane apparatus—construction and use. Agric. Eng., 28: 451–454.

Statistical Analysis Systems (SAS) Institute, Inc., 1988. SAS/STAT User's Guide, Release 6.03 edn. SAS Institute, Inc., Cary, NC.

Snedecor, G.W. and Cochran, W.G., 1980. Statistical Methods. Iowa State University Press, Ames.

Soil Survey Division Staff, 1993. Soil Survey Manual. US Dep. Agric. Agric. Handb. 18.

Soil Survey Staff, 1991. Soil survey laboratory methods manual. Soil Survey Investigations Rep. 42. USDA-SCS, Washington, DC.